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Fabrication of AZ31 alloy wire by continuous semisolid extrusion process

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Abstract: A novel technology of continuous semisolid extrusion Process (CSEP) was adopted to produce AZ31 alloy structural materials. Effects of technological conditions on the microstructures of AZ31 alloy during CSEP were studied. During the casting process, the non-uniform distribution of microstructures was found in the roll−shoe gap. Microstructure evolution from dendrite to rosette or spherical grains was observed during the casting process by CSEP. The results show that high casting temperature and large cooling intensity can cause non-equilibrium solidification region near the roll surface, large roll−shoe gap width and high cooling intensity can lead to the formation of discontinuous solidification microstructure and slip plane near the shoe surface, which will finally cause the failure of the casting process. The proper casting temperature range of 730−750 ˚C, the roll cooling intensity of 0.4 L/s and the roll−shoe gap width of less than 10 mm are suggested. Under the suggested conditions, the product with diameter of 10 mm of AZ31 alloy with smooth surface and homogeneous striped microstructure is obtained. The average strength of the product after heat treatment reaches 270 MPa, and the elongation is 16%.

Key words: continuous semisolid extrusion process; AZ31 alloy; technological conditions; microstructure; property

1 Introduction

In order to deal with the problems such as raw materials shortage and air pollution, many scientists try to develop new near-net-shape forming process[1−2]. Semisolid metal processing has many advantages, such as short process, high efficiency, energy-saving, materials-saving, good microstructures and properties. So, it has been highly evaluated and has been widely studied[3−5]. It was reported[6] that SCR process could prepare semisolid alloys through a single roll shearing and cooling. Based on SCR process, as a novel near-net-shape forming process, continuous semisolid extrusion process was developed[7]. As shown in Fig.1, the alloy melt is cast into the roll−shoe gap, the roll can rotate during the casting process, alloy is stirred by the roll and transforms to semisolid slurry, and an extrusion mould is installed at the exit of the roll−shoe gap. Semisolid slurry is filled into the mould through a narrow filling mouth and subsequently is extruded. The process has several advantages[8]: 1) manufacturing semisolid slurry and continuous forming as a single process is achieved, which is a great development compared with conventional thixoforming. 2) Due to flow uniformity and easy filling of semisolid alloy, the microstructures and properties of the product are excellent.3)Through continuous semisolid extending-extrusion, it is easy to produce large sectional bar.

Semisolid forming, especially rheoforming of magnesium alloys, is a relatively new subject and attracts more attentions[9−11]. Manufacturing flat bar and tube of alloy by CSEP has already been studied and a great achievements are obtained[7−8], but how to produce magnesium alloy materials by this process is completely a new subject. In this work, based on the self-made testing machine, continuous semisolid extrusion of AZ31 magnesium alloy for producing the round bar with diameter of 10 mm was investigated. Effects of technological conditions on microstructures of AZ31 alloy during CSEP were studied.

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2 Experimental

As shown in Fig.1[7], the testing machine mainly includes a rotating roll which was cooled by water, a stationary shoe and a set of forming mould. The roll is composed of inner roll and outer roll, and the cooling water flows between them. The forming mould was fixed in the shoe, and the shoe was fixed on the framework by lead screws. The diameter of the forming region is 10 mm**.** The melt of AZ31 alloy was refined at 790 ˚C and was carried to the testing machine, then the melt was cast into the roll−shoe gap under protection by argon. The casting temperature were varied from 690 ˚C to 790 ˚C. When the alloy was cast into the roll−shoe gap, the rotation roll imposed ceaselessly shear force on the melt,so strong internal friction force and shear stress occurred in the melt. The formed dendrites were sheared, so the alloy transformed into the semisolid slurry, and then, the slurry was drawn downward by the roll. The extrusion mould was designed and installed at the exit of roll-shoe gap; the semisolid AZ31 alloy was continuously extruded. So slurry preparation and extrusion were organically combined. The testing material is AZ31 magnesium alloy with solidus and liquidus of 542 ˚C and 635 ˚C, respectively.

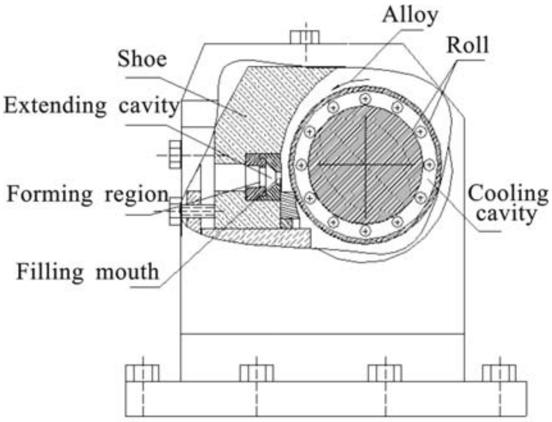

Fig.1 Schematic diagram of semisolid extending-extrusion assembly

After the roll stopped during casting operation, alloy remained and rapidly solidified in the roll-shoe gap and in the forming mould; the specimens were taken from different locations. After the specimens were polished and etched, the microstructures of the alloy was examined by optical microscopy. Microstructure formation and distribution were investigated. Through the experiment, technological conditions of CSEP were primarily optimized.

3 Results and discussion

3.1 Microstructure formation and distribution

Rosette grain formation was observed with the application of large force provided by the rough roll, as shown in Figs.2(a) and (c). During casting process, once the melt contacts the roll surface, alloy melt nucleates near the roll surface and dendritic crystals begin to grow. Being sheared by the roll, primary dendritic arms are broken into small fractions which disperse in the melt and change into seed crystals. While the seed crystals grow freely under shear by the roll, their structure changes. Owing to the fact that heat diffusion normal to the roll surface is dominant, grains prefer to grow along this direction[12]. However, in as much the roll is rotating during casting, the alloy is sheared by the friction force; in this case, dendrite arms are sheared off from main bodies at their roots. In addition, the grains are sheared and move freely with slipping and rotating, and this type movement causes continuous change of heat diffusion direction, which leads grain-growth direction to change continuously, namely, seed crystals have equal chance to grow in every direction, so grains prefer to grow into rosettes[13−14].

Fig.2 also shows the distributions of microstructure from the shoe surface to roll surface and from roll-shoe gap entrance to the roll-shoe gap exit. It is seen that the microstructure distributions are not uniform along the transverse or longitudinal directions in the roll-shoe gap. There are lots of big dendrites near the roll surface, and then, the microstructures evolve to spherical or rosette grains near the shoe. This behavior indicates that the alloy is not effectively sheared near the roll during casting. But the alloy is obviously sheared near the shoe. The reason is that the roll is cooled by water, but the shoe is not cooled, the water-cooled rollcan provide a strong cooling intensity, alloy melt is rapidly cooled by the roll, the nucleus can easily appear and the melt quickly solidifies near the roll, so the alloy near the roll can not be sheared at the semisolid state, correspondingly, the big dendrites are maintained in the solidification shell.

However, the melt near the shoe does not completely solidify yet and can be effectively sheared at the semisolid state by the rotating roll, so the spherical or rosette grains are maintained. It can also be seen from Fig.2 that as the alloy flows downward from the entrance to the exit of the roll-shoe gap, alloy microstructure near the shoe surface gradually evolves from rosette or dendritic grains to spherical or rosette grains. The reason is that the alloy is gradually sheared from the entrance to the exit; the dendrites can be broken up and spheroidized completely. Fig.3 also shows the same rule during casting at 690 ˚C. It is observed that the spherical grains

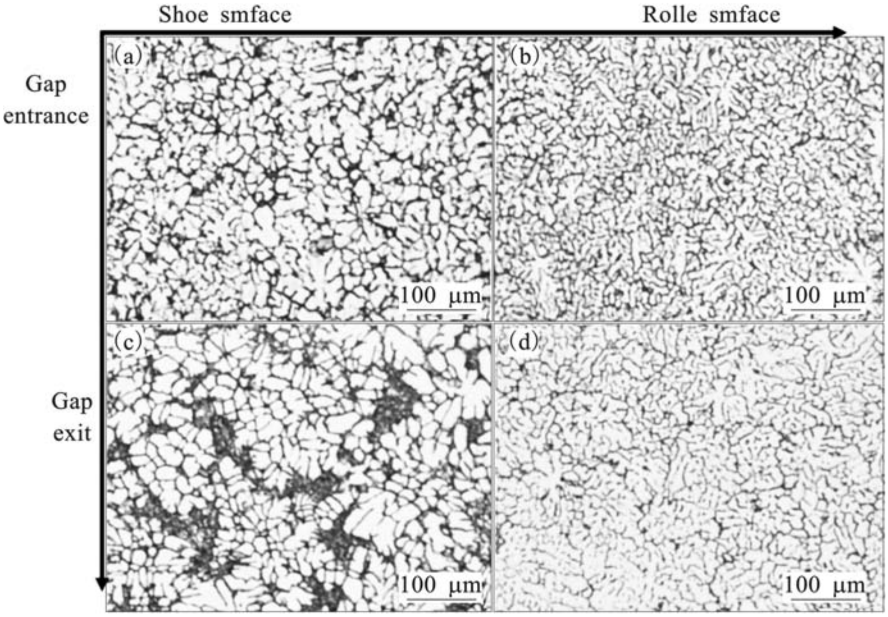

Fig.2 Microstructure distribution in roll−shoe gap when casting at 710 ˚C and cooling intensity (water flow velocity) of 0.8 L/s (arrows show microstructure evolution directions from gap entrance to gap exit and from shoe surface to roll surface)

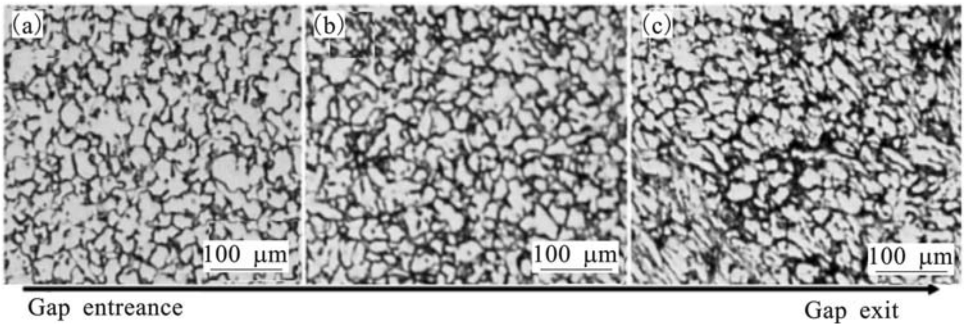

Fig.3 Microstructure evolution from gap entrance to gap exit neat shoe surface when casting at 690 ˚C and without water cooling (arrow shows microstructure evolution direction from gap entrance to gap exit)

are partly stretched and a part of the grains trend to flow along the flow line at the gap exit prior to the deformation mould.

3.2 Effects of technological conditions on microstructures

Casting temperature and cooling intensity have great influence on casting process. If the casting temperature is too low or the cooling intensity is too high, once the alloy melt contacts the roll surface, alloy will rapidly solidify, the solidification speed is so fast that the solute of the melt cannot completely diffuse in time, and the melt solidifies completely. In this case, the non-equilibrium solidification microstructure can be maintained as shown in Fig.4, the grain boundary is not clear and the second phase precipitates in the primary α phase. This kind solidification microstructure has a large strength and a bad plasticity. During the experiment, it is seen that the rapid solidification in the roll−shoe gap usually causes “wall slippage”, and therefore very little stirring efficiency can be obtained and results in deformation failure. As shown in Fig.4, metal flow or plastic flow becomes difficulty, and the product of AZ31 alloy cannot be obtained through CSEP. In some cases, even the product is obtained, the product surface is rough with some fractures. The microstructure difference under different cooling intensities are also shown in Fig.5. if the casting temperature is 730 ˚C and the cooling intensity is 0.8 L/s, feather grains are obtained near the roll surface; however, if the cooling intensity decreases to 0.4 L/s, the rosette or equiaxed grains are maintained.

The roll−shoe gap width and the property of the roll surface have great influence on the cooling intensity and shear strength of the alloy. It is easy to be understood. If the roll-shoe gap is narrow, the cooling intensity is large and the shear force on the alloy, is also large. Too wide gap will cause little shear force on the alloy especially near the shoe surface, and the alloy is not easy to be dragged to flow, so the deformation process cannot be achieved. At the same time, the melt is not stirred completely in the larger roll−shoe gap; the slurry microstructure is not good for deformation. So, the roll−shoe gap width should be properly controlled. The character of roll surface also affects solidification process. The rough roll surface can provide not only good matrix for heterogeneous nucleation but also large shear force for metal flow, so the roll−surface should be designed with a certain roughness. In addition, it is observed that the slip plane is in the roll-shoe gap, as shown in Fig.6. it can be seen that the alloy near the stationary shoe almost can not flow, but the alloy near the center of the gap obviously flows and the microstructure is stretched, the slip plane appears in the interface between two parts, as shown by arrow in Fig.6. Large roll-shoe gap width and high cooling intensity can lead to the formation of discontinuous solidification microstructure and slip plane near the shoe surface. If the roll-shoe gap width is too large, the slip plane will move to the shoe surface, which is harmful for slurry preparation and deformation process.

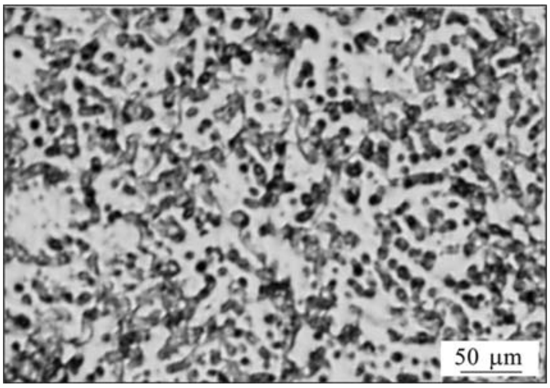

Fig. 4 Microstructure in roll−shoe gap entrance when casting at 750 ℃ and cooling intensity water flow velocity of 0.8 L/s

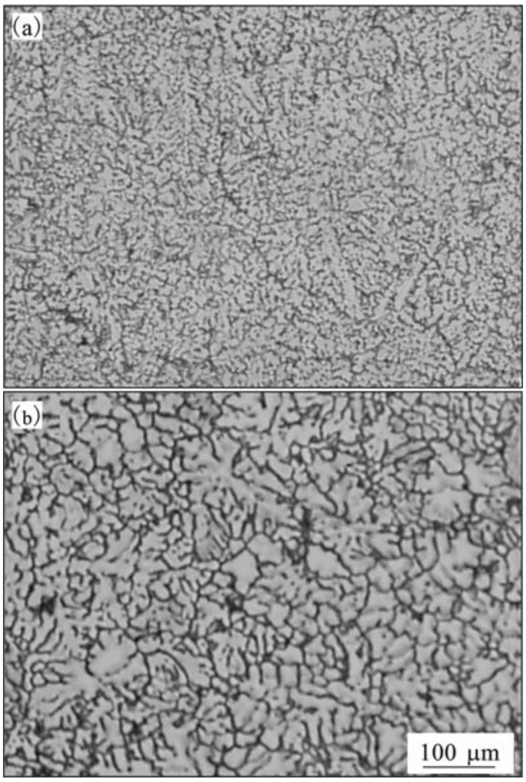

Fig.5 Microstructures in roll−shoe gap entrance near roll surface when casting at 730 ˚C and at different cooling intensities: (a) 0.8 L/s; (b) 0.4 L/s.

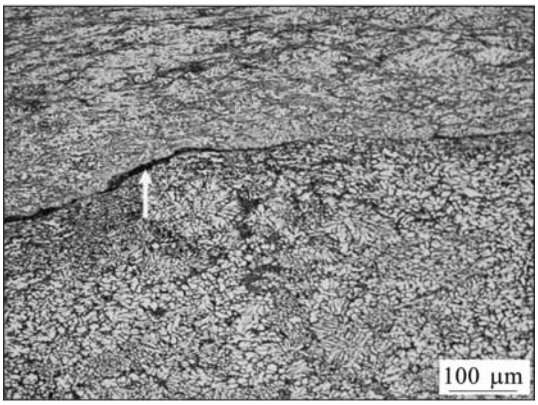

Fig. 6 Microstructure and slip plane near the shoe surface when casting at 750 ˚C and at the cooling intensity of 0.8 L/s

A proper casting temperature range of 730–750 ˚C, the roll cooling intensity of 0.4 L/s and the roll shoe gap width of less than 10 mm were suggested. Under the proposed conditions, the product with good smooth surface can be obtained, as shown in Fig.7. Its central microstructure along longitudinal direction is shown in Fig.8. It can be seen that the microstructure of the product obtained by CSEP is homogeneous with a striped appearance. The black striped microstructure forms from the solidification of liquid phase during the processing. The white phases are α base phases that are strongly stretched during the process. The remnant liquids correspondingly distribute along the solid phase boundaries and also show stripped lines.

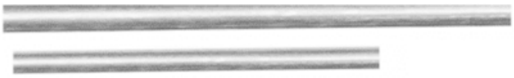

Fig. 7 Φ10mm AZ31 product obtained by CSEP

3.3 Effects of heat treatments on microstructure and property of product

Fig. 9 shows SEM microstructure and phase analysis at point *A*. After aging at 220 ˚C, many phases appear, the black matrix is α-Mg. The ompositions of white Phase at point *A* contain magnesium 57.832%, aluminum 42.168%, and the phase is the strengthening phase of β-$Mg_{17}Al_{12}$. The tensile test results show that the average strength of the product after heat treatment reaches 270 MPa, and the elongation is 16%, which can meet application requirements in some areas[15].

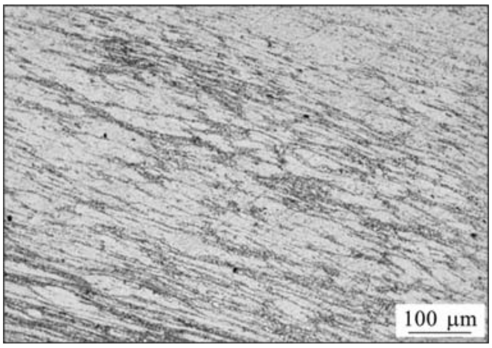

Fig.8 Central microstructure of AZ31 alloy product along longitudinal direction when casting at 750 ˚C

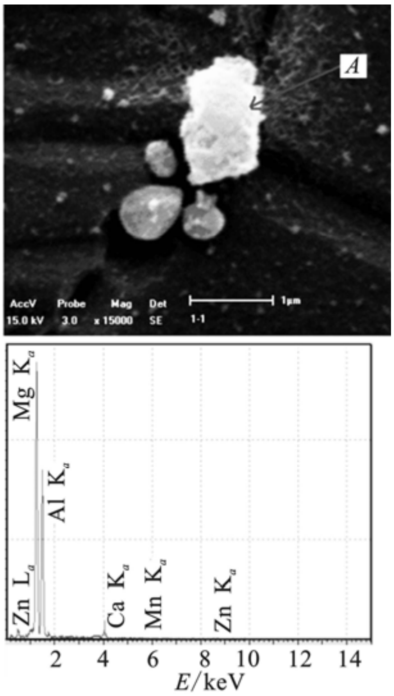

Fig.9 SEM microstructure and compositins at point *A* of product aged 220 ˚C for 24 h

4 Conclusions

1) A novel technology of continuous semisolid extrusion process (CSEP) is proposed and adopted to produce AZ31 alloy structural materials.

2) Effects of technological conditions on microstructures of AZ31 alloy during CSEP are studied. A proper casting temperature range of 730–750 ˚C, the roll cooling intensity of 0.4 L/s and the roll shoe gap width of less than 10 mm are suggested.

3) During the casting process, non-uniform microstructure distribution is found in the roll−shoe gap. Microstructure evolution from dendrite to rosette and spherical grains is observed during the casting process by CSEP.

4) Under the suggested conditions, the product with diameter of 10 mm of AZ31 alloy with smooth surface and homogeneous striped microstructure is obtained. The average strength of the product after heat treatment reaches 270 MPa, and the elongation is 16%.

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